

Upper limits on neutrino masses from cosmology

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Upper limits on neutrino masses from cosmology have been reported recently to reach the impressive sub-eV level, which is competitive with future terrestrial neutrino experiments. In this brief overview of the latest limits from cosmology I point out some of the caveats that should be borne in mind when interpreting the significance of these limits.

1. Introduction

The latest results from the WMAP satellite [1] confirm the success of the Λ CDM model, where $\sim 75\%$ of the mass-energy density is in the form of dark energy, with matter, most of it in the form of cold dark matter (CDM) making up the remaining 25% . Neutrinos with masses on the eV scale or below will be a hot component of the dark matter and will free-stream out of overdensities and thus wipe out small-scale structures. This fact makes it possible to use observations of the clustering of matter in the universe to put upper bounds on the neutrino masses. An excellent review of the subject can be found in [3]. With the improved quality of cosmological data sets seen in recent years, the upper limits have improved, and some quite impressive claims have been made in the recent literature. I will in the following summarize the latest upper bounds and point out some of the potential systematic uncertainties that need to be clarified in the future.

2. Current constraints on neutrino masses

One of the assumptions underlying cosmological neutrino mass bounds is that neutrinos have no non-standard interactions and that they decouple from the thermal background at temperatures of order 1 MeV. In that case, the relation between the sum of the neutrino masses M_ν and their contribution to the energy density of the universe is given by $\Omega_\nu h^2 = M_\nu/93.14$ eV [2], where h is the dimensionless Hubble parameter defined by writing the Hubble constant as

$H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$. The 95% confidence upper bounds range from ~ 2 eV from the CMB alone ([7], see also [8]) to 0.17 eV from a fit to CMB, SNIa, and large-scale structure, including the Lyman α forest [9]. The tightest limits in the table are quite impressive, and with limits reaching deep into the sub-eV region it is prudent to point out that there are systematic uncertainties associated with these limits. I will in the following discuss briefly two different types of uncertainties: cosmological uncertainties (models and priors) and astrophysical uncertainties (e.g. galaxy-dark matter bias).

Reference	M_ν -bound
Elgarøy et al. 02[4]	1.8 eV
Sánchez et al. 05[5]	1.2 eV
Goobar et al. 06[6]	0.62 eV
Fukugita et al. 06[7]	2.0 eV
Spergel et al. 06[1]	0.68 eV
Seljak et al. 06[9]	0.17 eV
Kristiansen et al. 06[10]	1.4 eV

Table 1

Some recent cosmological neutrino mass bounds (95 % CL).

3. Uncertainties in the underlying model

Most of the limits in table 1 are derived under the assumption that the underlying cosmological

model is the standard spatially flat Λ CDM model with adiabatic primordial perturbations. Slight variants have been considered, e.g. running spectral index of the primordial perturbation spectrum [9] and varying equation of state parameter w for the dark energy component [6,11]. A significant degeneracy between w and M_ν was pointed out by Hannestad [11]. This degeneracy is a result of the fact that the matter power spectrum depends on $f_\nu = \Omega_\nu/\Omega_m$, and allowing w to vary weakens the constraints on Ω_m and hence indirectly on $M_\nu \propto f_\nu \Omega_m$. The degeneracy can be broken by including constraints from e.g. baryon acoustic oscillations [12] as shown in [6], or, quite simply, by using better data ([8,13]).

The spatially flat Λ CDM model describes the existing cosmological data well, but we are not yet in a position to exclude significant variations. For example, models where gravity is different from standard Einstein gravity are still viable, and that might change the neutrino mass limit significantly (see e.g. [14]) for an example).

The CMB is a very clean cosmological probe in the sense that the extraction of the anisotropy signal from the data involves relatively few and well justified astrophysical assumptions. From this point of view the upper mass bound of 2 eV at the 95 % confidence level from the CMB data alone found by Fukugita et al. [7] is the most robust one. However, if one extends the space of models investigated to models that are very different from Λ CDM, there is no upper bound on neutrino masses from the CMB. To demonstrate this point, I point out that Blanchard et al. [15] found that an Einstein-de Sitter model with $M_\nu = 2.4$ eV gave an excellent fit to the WMAP data, provided that there are oscillations in the primordial power spectrum, as produced e.g. if there is a phase transition during inflation. Now this model has both a low Hubble parameter ($h = 0.46$), no cosmological constant (and hence a bad fit to the supernovae type Ia data), and is also in some tension with the baryonic acoustic oscillations, but this goes to show that the CMB alone cannot produce a constraint on the neutrino mass once one allows for more radical departures from Λ CDM.

To get really tight constraints on the neutrino

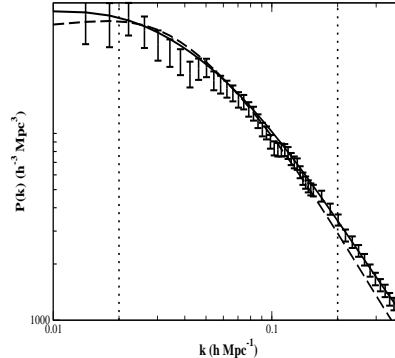


Figure 1. The power spectrum of the full 2dFGRS (bars) along with models with $f_\nu = 0$, $\Omega_m h = 0.168$ (full line) and $f_\nu = 0.18$, $\Omega_m h = 0.38$ (dashed line).

masses, one needs to include large-scale structure data, since the CMB alone cannot go much below 2 eV in sensitivity. It is, however, worth nothing that large-scale structure alone cannot do the job. Take the 2dFGRS power spectrum as an example. Figure 1 shows the power spectrum of the full 2dFGRS survey as determined by Cole et al [16]. Figure 1 also shows the power spectra for a model with no massive neutrinos and $\Omega_m h = 0.168$, and for a model with $f_\nu = 0.18$ and $\Omega_m h = 0.38$. These two models have identical values of the χ^2 for the data in the range used in fits, marked by the dashed vertical lines in the figure. Thus, one can still hide a lot of neutrinos in the matter power spectrum when one does not make use of external constraints on Ω_m .

4. Astrophysical systematics: bias

Galaxy redshift surveys measure the distribution of galaxies in the local universe. The relation between the distribution of the luminous matter and the dark matter is therefore an important issue when estimating cosmological parameters in general, and the neutrino mass in particular (see

e.g. [17] for an overview). The usual assumption is that the power spectrum of the matter distribution is proportional to the galaxy power spectrum on scales in the linear regime, so-called constant bias. However, recent results [5,10,18] indicate that there are inconsistencies between the results obtained by combining the WMAP data with the 2dFGRS power spectrum, and those obtained by combining WMAP with the SDSS power spectrum obtained in [19]. One of the possible interpretations of this result is that the bias is scale-dependent [18]. In any case, this is an important issue to clarify. Ideally, one would like to have a direct probe of the mass power spectrum. The cluster mass function, with cluster masses derived directly from weak gravitational lensing is one such probe, and was obtained for the first time in [20]. In [10] this mass function was combined with the WMAP 3-year data to obtain a 95% upper limit $M_\nu < 1.4$ eV. Although not as impressive as other bounds, this limit is robust in the sense that no assumptions about bias were made in deriving it.

5. Summary

Current cosmological observations provide strong upper limits on the sum of the neutrino masses. However, when assessing the significance of these limits one should bear in mind that several assumptions are involved in deriving these limits, both cosmological and astrophysical. It is an important task for further research to clarify how sensitive the results are to these assumptions, and how well they are justified.

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